Physica C 470 (2010) 874–876

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Proximity effect as a probe of electronic correlations and exchange field in ferromagnet/superconductor nanostructures

Yurii Proshin *, Marat Khusainov, Mansur Khusainov

Kazan State University, Kremlevskaya str., 18, Kazan 420008, Russia

ARTICLE INFO

Article history:
Available online 20 February 2010

Keywords:
Proximity effect
Superconductor
Ferromagnet
Critical temperature
Layered nanostructures
Electronic correlations
Exchange field
The FFLO state

ABSTRACT

The proximity effect for thin bilayer F/S and trilayer F/S/F, where F is a ferromagnetic metal, and S is superconductor, is investigated on the base of new boundary-value problem for the Eilenberger function. For both systems the dependencies of critical temperature on an exchange field of the F metal, electronic correlations in the S and F metals, and thicknesses of layers F and S are derived. It is shown that the possibility of the Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) state observation is especially increased in the asymmetrical trilayers F/S/F$'$ for which solitary reentrant superconductivity is predicted. We propose new method of probe of electronic correlations and exchange field. It allows us to predict the sign and value of the constant of electron–electron interaction in gadolinium and to explain a surprisingly high critical temperature ($T_c \sim 5$ K) in the short-periodic Gd/La superlattice.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

The competition of superconducting and magnetic states for the layered ferromagnet/superconductor (F/S) nanostructures leads to the number of various nontrivial phenomena at the proximity effect condition (see reviews [1–4] and references therein). Superconductivity in the F/S nanostructures is a superposition of the BCS pairing with zero total momentum in the S layers and the Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) [5] pairing with nonzero three-dimensional (3D) coherent momentum in the F layers. As a rule a superconductivity occurs at $d_f \ll d_s$, where $d_{f(s)}$ is the F(S) layer thickness. The typical case is the layered Gd/Nb and Fe/V structures [1–4]. However, the three-dimensional superconductivity in the Gd/La superlattice not only exists at $d_f > d_s$, but appears at T_c equal to the critical temperature of a bulk lanthanum sample [6].

To explain this surprising phenomenon we develop the nontrivial three-dimensional theory of the proximity effect with the inclusion of electron–electron interactions responsible for superconductivity not only in the S layers, but also in the F layers. It allows us to propose a peculiar kind of spectroscopy based on the proximity effect.

2. Main formalism

We consider the pure BCS superconductor layer S ($0 < z < d_s$), located between two pure ferromagnets F and F$'$, occupying fields $-d_f < z < 0$ and $d_s < z < d_s + d_f'$, respectively. Everywhere the parameters and functions of layers S(F) are denoted by subscripts $s(f)$, belonging to the layer F$'$ is indicated by prime. The thickness d_f' can be varied at fixed thickness d_f. The case $d_f = 0$ and $d_f' \neq 0$ corresponds to the S/F$'$ bilayer.

According to symmetry of layered structures it is convenient to make partial Fourier transform on $\vec{\rho}$ [1,7] ($\vec{\rho}$ is component of radius-vector $\vec{r}$ perpendicular to the z-axis). The self-consistency Gor'kov equation and differential equation for the Eilenberger function $\Phi(\vec{p}, \vec{q}, z, \omega)$ for layers S(F) look like [8]

$$\Delta_{s(f)}(\vec{q}_{s(f)}, z) = 2\lambda_{s(f)}\pi T \mathrm{Re}\sum_{\omega>0}{}^{'}\langle \Phi_{s(f)}(\vec{p}, \vec{q}_{s(f)}, z, \omega)\rangle; \quad (1)$$

$$\left[2\tilde{\omega}_{s(f)} - v_{s(f),z}\xi_{s(f),z}\frac{\partial^2}{\partial z^2}\right]\Phi_{s(f)}(\vec{p}, \vec{q}_{s(f)}, z, \omega) = 2\Delta_{s(f)}(\vec{q}_{s(f)}, z), \quad (2)$$

$$\xi_{s(f),z} = \frac{v_{s(f),z}}{2\tilde{\omega}_{s(f)}}; \quad 2\tilde{\omega}_s = 2\omega + i\vec{q}_s\vec{v}_{s,\perp};$$
$$2\tilde{\omega}_f = 2\omega + i(2I + \vec{q}_f\vec{v}_{f,\perp}), \quad (3)$$

where $\Delta_{s(f)}$ is the three-dimensional order parameter, I the exchange field in the ferromagnets, $\lambda_{s(f)}$ the electron–electron interaction constant, the prime at the sum sign means a cutoff at the Debye frequency ω_D; $\omega = \pi T(2n+1)$ the Matsubara frequency, T the temperature, $\vec{v}_{s(f)}(\vec{v}_{s(f),\perp}, v_{s(f),z})$ the Fermi velocity with its projections and we suppose $\hbar = k_B = \mu_B = 1$ hereinafter. The integration on $\vec{p}$ over the total solid angle of the Fermi sphere are determined by $\langle \ldots \rangle$. The two-dimensional components of the FFLO pairs

* Corresponding author.
E-mail address: Yurii.Proshin@ksu.ru (Y. Proshin).

0921-4534/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.physc.2010.02.065